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Constraints on the Stellar Populations of Elliptical Galaxies from Ultraviolet Spectra

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Abstract. We present preliminary results from spectral synthesis models of old stellar populations for the spectral range 912-4000 Å with ~ 10 Å resolution, which can be used to investigate the UVX phenomenon and to assess ages and abundances. Model spectra incorporating extreme horizontal branch (EHB) and Post-Asymptotic Giant Branch (P-AGB) populations give good matches to the far-UV spectra of galaxies. These models indicate an EHB fraction which is $< 10\%$ of the total HB population in all but the most extreme examples of the UVX phenomenon, where the EHB fraction is still $\leq 20\%$. Once the hot component that gives rise to the UVX phenomenon is accounted for, the mid-UV wavelength range ($2200 < \lambda < 3300$ Å) provides information about the age and metallicity of the underlying stellar population. The flux in this spectral range arises mainly from stars close to the main sequence turnoff. We compare models with the spectrum of M31 and discuss UV features which should be useful as population diagnostics.

1. Introduction

We present the results of our continuing investigation of ultraviolet radiation from old stellar populations. In this paper, we discuss the far-UV upturn phenomenon and point out the advantages of the long wavelength end of the vacuum UV window (the so-called "mid-UV", $2000 \lesssim \lambda \lesssim 3300$ Å) for determining the age and abundance of the bulk stellar population.

The sources most widely held now to be responsible for the far-UV upturn (or UVX) phenomenon are extreme horizontal branch (EHB) stars (e.g. Burstein et al. 1988; Greggio & Renzini 1990; Dorman, Rood, & O'Connell 1993, hereafter Paper I; Dorman, O'Connell, & Rood 1995, hereafter Paper II, and references therein). Unfortunately, the production of these stars occurs through mass loss processes in cool giants, which remain ill-understood and unpredictable with our current understanding of stellar evolution. Changes of only a few $0.01 M_\odot$ in envelope mass can strongly affect the far-UV output of hot HB stars. In contrast, the mid-UV flux is dominated by the turnoff population, which responds strongly to the age and abundance of the underlying stellar population. This region can therefore potentially provide us with population indicators

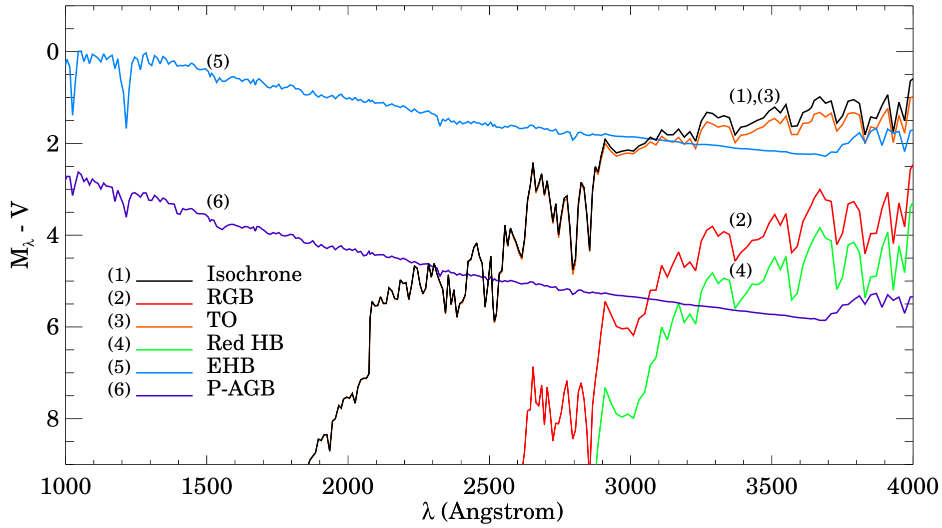

Figure 1. Components of an old stellar population in the ultraviolet. Illustrated is a model with [Fe/H] $= 0$ at 10 Gyr. The pre-He flash component is represented by three separate lines: (1) the total light; (2) the giant branch [$T_{\rm eff} \leq 5000\,{\rm K}, L > L_{\rm TO}$]; and (3) the turnoff [$T_{\rm eff} > 5000\,{\rm K}$]. The maximum possible contributions due to red HB stars (4), EHB stars (5), and P-AGB stars (6) are also shown (see section 2.).

that suffer less from the well-known degeneracies found at optical wavelengths (e.g. Worthey 1994 and this meeting).

We illustrate the UV spectra of components of old metal-rich stellar populations in Fig.1, plotted in magnitudes normalized at V. These are based on the same evolutionary models discussed in Paper II, but we have now added spectral energy distributions using full resolution model stellar fluxes taken from the Kurucz (1993, CD-ROM) grid. The maximum possible P-AGB and EHB contributions are shown to the same scale; each of these would be realized if *all* post-RGB stars went through that particular channel. Note that the most obvious difference between (5) and (6) is in the strength of the Lyman series, allowing a possible diagnostic for the relative contributions of these two hot sources.

The most striking feature of this diagram is that the turnoff flux dominates the contribution from the earlier stages of evolution at all wavelengths shortward of 4000 Å; the continuum produced by the cool giants is about 2 mag below that of the turnoff (compare Buzzoni 1989 and Worthey 1994). Thus the mid-UV spectrum ($\lambda > 2000$ Å) derives almost entirely from the turnoff and from the hot component that gives rise to the UVX phenomenon (Burstein et al. 1988). If the spectrum emanates solely from old stars, then the mid-UV radiation can be corrected for the UVX component to yield important information about the bulk stellar population.

2. The Far-UV ($912 < \lambda < 2000$ Å)

The galaxies with the strongest manifestations of the UV upturn phenomenon (NGC 1399 and NGC 4649 $=$ M60), with $m_\lambda(1500\text{Å}) - V = 15{-}V \lesssim 2.5$ have rightly received a great deal of attention. However in most of the ellipticals so far observed, $3 < 15{-}V < 4$. The evidence gathered in the last few years by HST, UIT and HUT has all but ruled out young massive stellar components as the explanation for the UV spectra of these galaxies (Paper II). In the 'strong UVX' systems the radiation also cannot be explained by the hot sources — post Asymptotic Giant Branch (P-AGB) stars, including planetary nebula nuclei— that must be present in old, passively evolving stellar populations (Greggio & Renzini 1990). In the 'weaker UVX' cases $(15{-}V > 3.5)$, however, an explanation in terms of the 'classical' P-AGB stars is plausible given the remaining uncertainties in the stellar models.

The stellar populations of the Galactic field are however found to contain other types of UV-bright stars. The Palomar-Green survey of UV excess sources (Green, Schmidt, & Liebert 1986) is dominated by the Galactic subdwarf B and O stars (see Saffer & Liebert 1995 for a recent study), which are apparently produced by extreme mass loss in single stars. These are the observed counterparts of the EHB stars and of their post-HB descendants, the AGB-manqué objects (Paper II). While they appear to be a natural extension of the horizontal branch sequence seen in metal-poor clusters, this may not be the full explanation. Both in the Galactic field and in the few globular clusters where they have been found (ω Cen: Whitney et al. 1994; NGC 6752: Buonanno et al. 1986), they appear to form a distinct group separated by a temperature gap from the blue HB stars. This may indicate the action of a different, more vigorous mass loss process at work in some stars.

The simplest explanation for the variation in the UV upturn strength is a variation in the number of EHB stars present. The correlation of the UVX with metallicity (Burstein et al. 1988 & references therein) then arises if more stars suffer high mass loss at high Z. In order to gauge whether this explanation is plausible, it is important to make quantitative estimates of how many such stars need to be present as a fraction of the entire post-red giant population. The answer to this question depends on two main factors: first, the UV energy radiated in the lifetime of the putative sources, and second, how many of them are created in unit time (the 'birth rate' of HB stars).

The far-UV colors of globular clusters in which nearly all of the HB stars contribute to the ultraviolet flux are $15{-}V \sim 1.6$. In the bluest galaxy, $15{-}V \sim 2$. Thus if the originating stars are similar, then number of sources radiating in the UVX galaxies is a significant fraction of the total number of HB stars present. This argument depends on the fact that both the lifetime radiated UV flux from core He-burning stars (Paper I) and their 'birth rate' (Paper II) are relatively insensitive to composition. The inference is that the sources responsible for the UV flux in the strongest cases are not drawn from a trace (i.e. $\ll 5\%$) population, such as the stars of the extreme metal-rich tail of the Z distribution. The UV flux from HB stars is bounded by the Fuel Consumption Theorem (Tinsley 1980; Renzini & Buzzoni 1986). The energy radiated in the far-UV depends on the helium burnt in the core, which varies little with composition. To be sure, during the HB phase hydrogen shell burning can also be significant, but if the star is hot enough to be a strong UV source the H-shell energy is comparable or (usually) much less than that produced by the helium core source. This bounds the total UV energy output from objects of similar helium core mass (see Paper I).

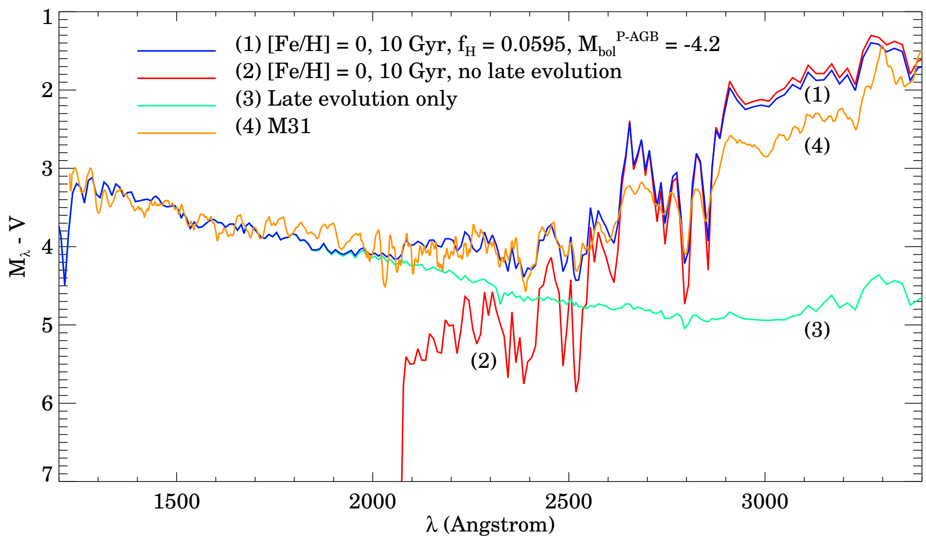

Figure 2. A fit to the UV/Optical spectrum of M31 using the two component model (1) of the HB. A solar metallicity isochrone spectrum (2) is assumed for the earlier, pre-He flash stages ("late" refers to the HB phase and beyond). The hot component (3) represents a uniform distribution of EHB stars that has been scaled to match the integrated far-UV flux from the M31 bulge, with $f_{\rm H} \sim 0.06$; the rest of the HB clump stars are assumed to become AGB stars and P-AGB stars. Note the match between the data and the model at the Fe II feature around 2400 Å and the Fe II and Mg I lines around 2500 Å. Also note the prominent Mg I and Mg II features at 2852 and 2800 Å respectively (see section 3.).

In Paper II we used a simple model of post-RGB phases to estimate the fraction $f_{\rm H}$ of the total HB population which is on the EHB in various observed objects. For objects with the strongest upturns we obtained $f_{\rm H} \sim 0.2$. In other words a significant, but not dominant, portion of the population is responsible for the UV upturn. With extreme composition assumptions, e.g. $[{\rm Fe/H}] = 0.7, Y = 0.46$, we found $f_{\rm H} = 0.10$, the difference arising from the more rapid evolution (and thus higher evolutionary flux) of helium rich models rather than from the higher metallicity. (Note that although the helium abundance Y corresponding to high metallicities is unknown, Y is unlikely to exceed its solar value by a large percentage, because the iron is produced by stars that produce little helium.)

3. The Mid- and Near-UV ($\lambda > 2000$ Å)

Figure 2 illustrates the potential utility of the longer UV wavelengths as population diagnostics. The fraction of EHB stars in the composite model [curve (1)] has been scaled so that its $15-V$ color matches that of the bulge of M31 as measured by IUE. We have chosen M31 [curve (4)] for comparison because its spectrum has high S/N and its far-UV flux ($15-V \sim 3.5$) is typical of elliptical galaxy nuclei. The figure shows that the contributions of the turnoff stars [curve (2)] and the hot UVX component are roughly equal for M31 at 2400–2500 Å. The strong lines in the turnoff component

are diluted by the UVX stars in the composite. The caption lists some of the mid-UV spectral features that are strong in G dwarf spectra that also appear in the galaxy spectra. Note in particular that the well-known Mg features around 2800 and 2850 Å, being of different ionization stages, may become a useful indicator of the turnoff temperature and may provide constraints on the age and metallicity[1] .

The turnoff spectrum has a break at 2100 Å; the location of this break is a strong function of metallicity (Paper III). Hence the fact that the IUE spectrum exceeds slightly the prediction from the hot component shortward of this point may indicate the presence of a more metal-poor component. Of some considerable interest is the obvious discrepancy between the M31 spectrum and the model in the range $3000 < \lambda < 3300$ Å. We find a similar flux deficiency in this spectral range in other galaxies (NGC 3379, NGC 4649). Such a deficiency is also present in the spectrum syntheses of Magris & Bruzual (1993), which were constructed with empirical fluxes. This is just at the point where IUE and ground-based datasets overlap, and the problem may be in the calibration. If these possibilities can be excluded, the next most likely explanation is a localized metallic overabundance in M31.

4. Future Work

The UV offers promising advantages for the study of old populations. UV broad-band indicators, which can be used for much fainter objects, should be developed into useful diagnostics. At moderate redshifts ($z \sim 1$) the mid-UV region is redshifted into the range of ground-based optical spectroscopy. The age dependence of the UV upturn phenomenon is difficult to calibrate since it depends on the luminosity-age relation of the P-AGB phase and critically on the details of giant branch mass loss. But one might expect that it should decrease in intensity with lookback time since in younger populations the P-AGB stars should be shorter-lived and the amount of mass loss required to produce EHB stars is greater. Without the hot component the detection and interpretation of the turnoff population at significant lookback times becomes easier. If mid-UV spectra can be used to help separate the age and metallicity of stellar populations, then we may be able to apply such techniques to populations at significant redshift. This may ultimately do much to resolve the apparent contradiction between the distance scale estimates of the age of the universe and those from stellar evolution.

However, the correct interpretation of such observations will be impossible without an adequate exploration of nearby galaxies from space in the UV. The observational database (e.g. Fanelli et al. 1992; Wu et al. 1991) of UV spectra of the stars that dominate the turnoffs of old stellar populations, namely late F and early G dwarfs, needs to be improved for a well-calibrated grid of metal abundances, especially at wavelengths below 2600 Å. Fig 2 also illustrates some of the deficiencies in the Kurucz synthetic spectral atlas used to derive the synthetic models: for example, the sharp peak at 2600 Å which is not present in the galaxy data or in IUE spectra of cool stars. In addition a set of nearby galaxy spectra out to Lyman α with higher resolution and S/N than present in the IUE atlases would be a valuable reference for conducting observational cosmology.

[1] The Mg II feature may be affected by chromospheric emission, but this is thought to be primarily a feature of younger late-type stars: see Smith et al. 1992

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